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BORA ON THE NORTHERN ADRIATIC COAST DURING THE ALPEX SOP 20-25 MARCH 1982
Bura na sjevernom Jadranu za vrijeme ALPEX SOP, 20-25. ožujka 1982.

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Abstract: Results from investigation of the bora during the period of 20-25 March 1982 are characterized by a large variability od bora strength, direction and duration.

The two distinct wind speed maxima indicate two different origins of bora genesis. The first bora (21 March) was caused by a cold air stream, followed by the Genova cyclogenesis process. The second bora situation (23-25 March) is connected with the central Europe anticyclone and the cold NE flow - upstream of the Dinaric Alps.

Assuming that the bora has a certain similarity with the supercritical flows described by hydraulic theory, the parameters of the real flow could be successfully predicted on the entire northern Adriatic in the case with the strongest bora.

K e y w o r d s: bora layer, hydraulic theory, ALPEX SOP, temperature inversion

Sažetak: Prikazani rezultati istraživanja bure na sjevernom Jadranu za vrijeme ALPEX SOP u razdoblju 20-25.03.1982. pokazuju veliku promjenljivost u jačini, smjeri i trajanju bure.

Dva odvojena maksimuma brzine vjetra ukazuju na dva različita uzroka nastanka bure. Prva bura (21.03.) uvjetovana je prodorom hladnog zraka u zapadno Sredozemlje i formiranjem Genovske ciklone. Druga bura (23-25.03.) povezana je s jačanjem anticiklone nad srednjom Evropom i hladnim NE strujanjem u navjetrini Dinarida.

Pod pretpostavkom da je bura atmosferski mezoskalni proces, koji ima određene sličnosti sa superkritičnim strujanjem, koje opisuje hidraulička teorija, uspoređeni su parametri stvarnog toka s teoretski prognoziranim vrijednostima. Pokazano je da se hidraulička teorija Smitha (1985) može primijeniti na područje sjevernog Jadrana u slučaju jake bure.

K l j u č n e r i j e č i: sloj bure, hidraulička teorija, ALPEX SOP, temperaturna inverzija.

1. INTRODUCTION

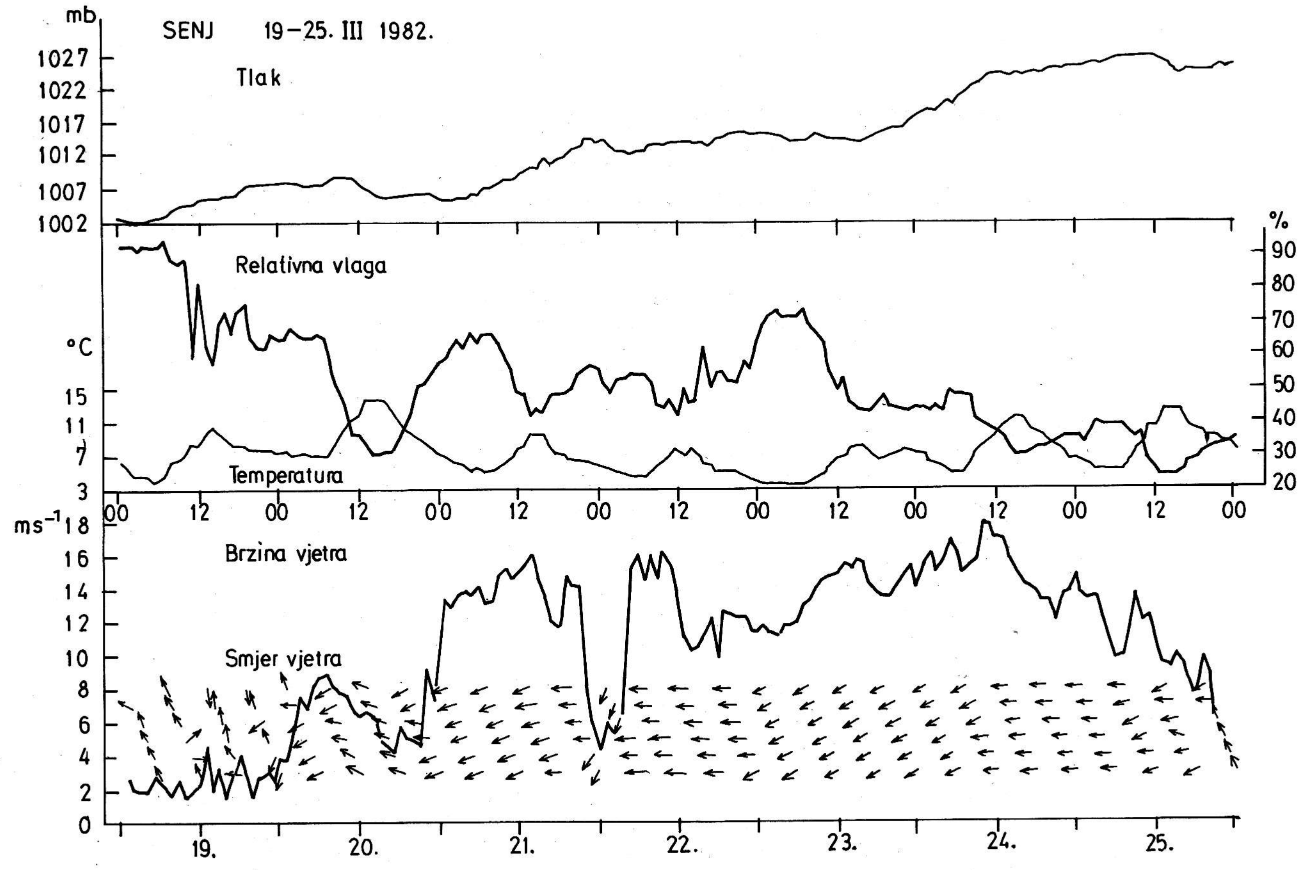
The results of bora investigations during the ALPEX SOP, 20-25 March 1982, are presented. Two days, 22 and 25 March, were covered by areal observations, as described by Smith (1987). For each cross section flown by the ALPEX research aircraft four panels are shown: horizontal wind field, potential temperature, moisture variable and turbulence intensity taken as the vertical velocity variance. Zagreb and Karlovac soundings are included on each cross-section.

The time interval under consideration here presents the largest time variability in gusts (Vučetić, 1984). The bora situation of the last day, 25 March, characterized by lower wind speeds and the NE winds throughout the troposphere, shows similarities to the ALPEX case of 28 and 29 April (Tutiš, 1988).

The existing analyses of the 20-25 March period apply only to the bora on the northern Adriatic Coast. However, the bora appeared also on the southern Adriatic Coast about 12 hours later.

Fig 1. shows the daily courses of mean hourly values of pressure, relative humidity, temperature, wind speed and direction for Senj, Rijeka airport (Omišalj), Split and Dubrovnik. Despite similarities in the strength and speed, the differences between bora on the southern and northern coast are considerable (especially in continuity of the wind velocity and direction). The southern coast bora reaches its maximum in the night and toward morning, while ceasing or completely disappearing during the day.

Some general features of the bora are well known pointing to large scale interaction processes (Jurčec, 1981). The NE cold air stream moving around the eastern Alps is further modified and enhanced by new blocking action on the windward side of the Balkans mountains. The flow across these mountains would affect the bora structure in the lee side directly. Therefore, in principle the mechanism of the northern and southern coast bora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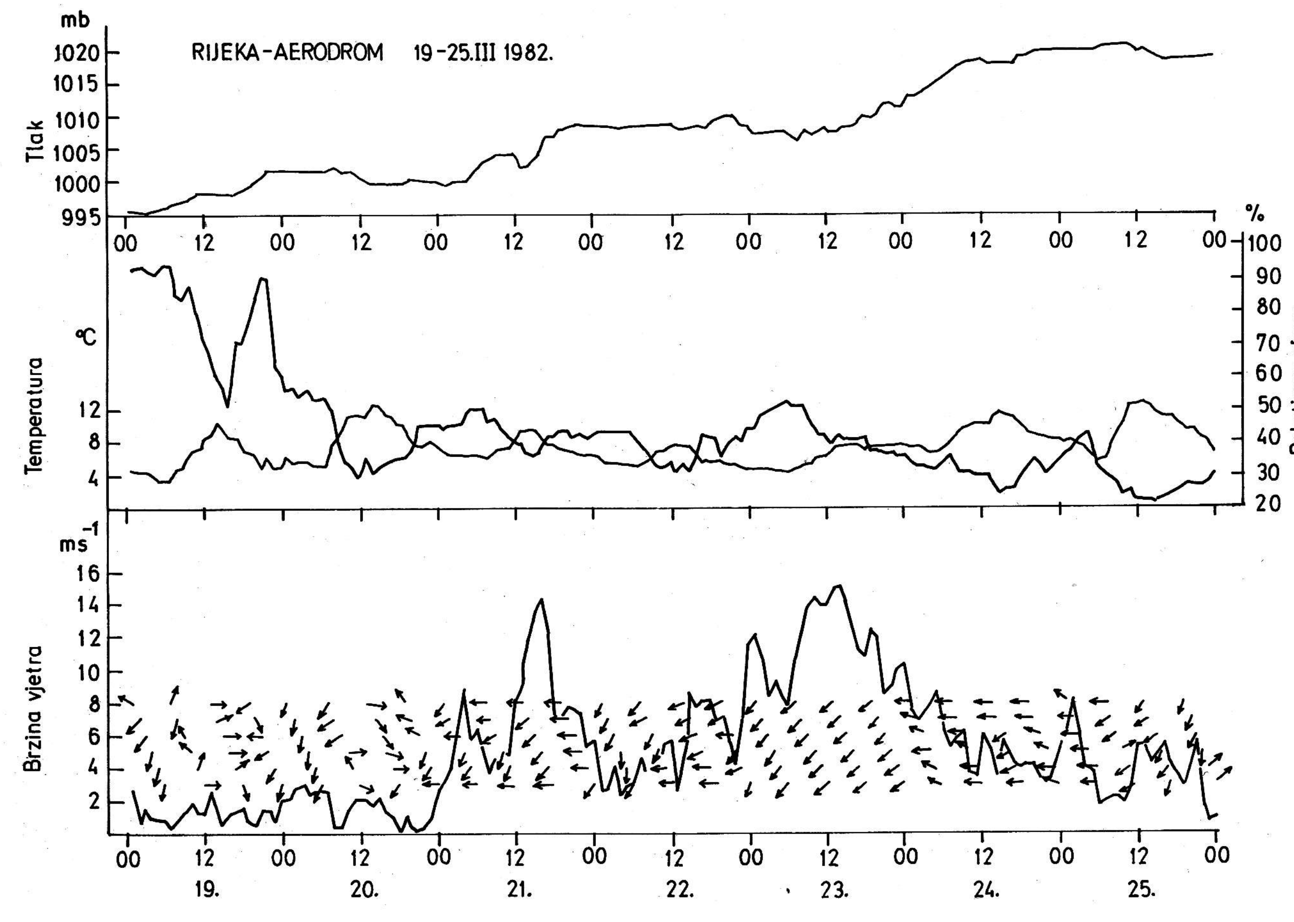
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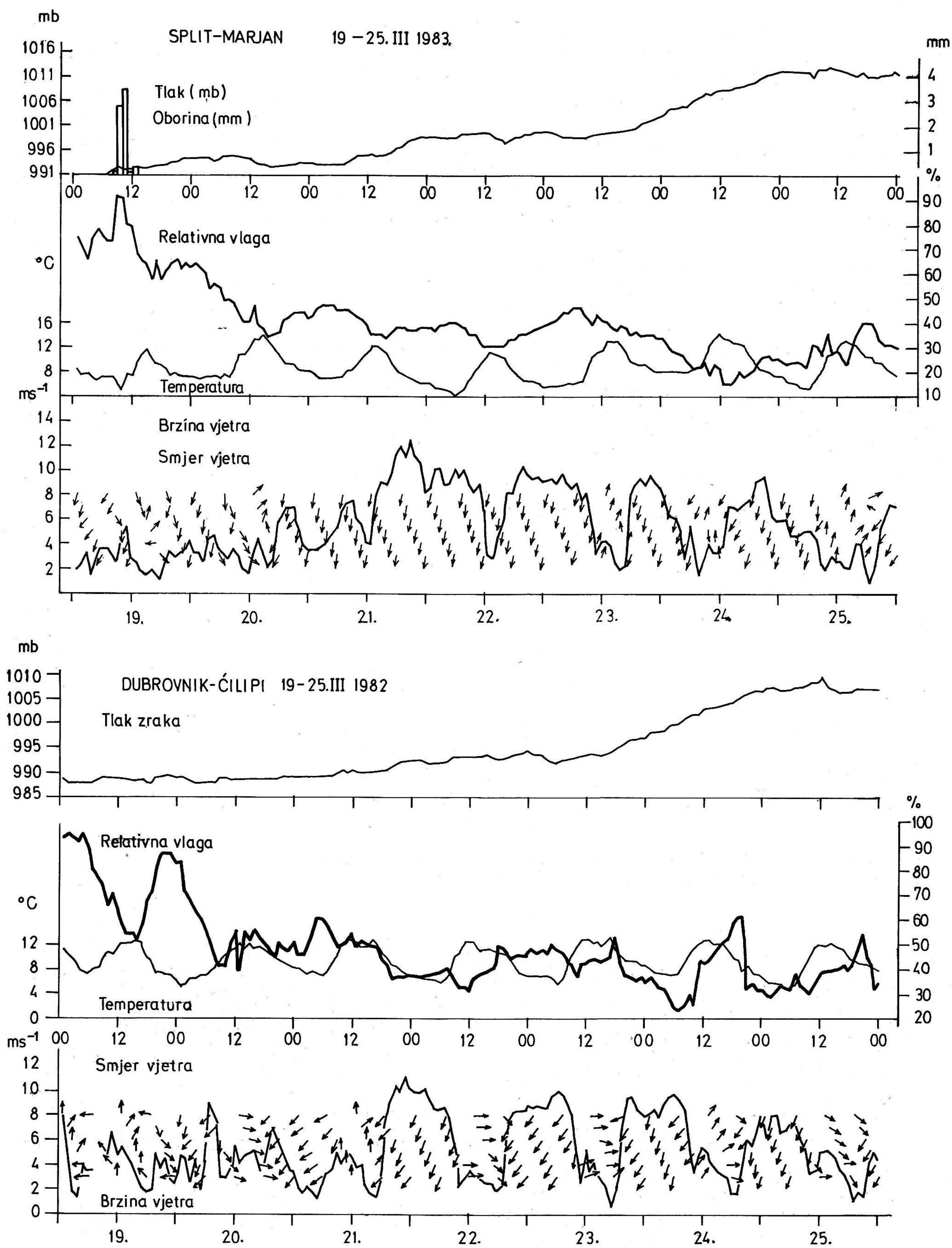

Fig. 1. Daily courses of mean hourly values of pressure, relative humidity, temperature, wind speed and direction for Senj, Rijeka-Omišalj, Split and Dubrovnik, 19-25 March 1982.

Sl. 1. Dnevni hodovi srednjih satnih vrijednosti tlaka, temperature, relativne vlage, brzine i smjera vjetra za Senj, Rijeka-Omišalj, Split i Dubronik, 19-25.3.1982.

might be different and require further analysis.

The results presented here are based on soundings in the upstream (Zagreb) and downstream (Pula) region, as justified by a previous analysis by Pettre (1984).

2. BORA SPACE AND TIME VARIATION

The bora in the night of 20/21 March started simultaneously at all places over the norther Adriatic area. Still, their intensity and duration depended very much on the particular location. As usual, the longest bora duration was in Senj. Two distinct wind velocity maxima are registered on 21 and 23/24 March, respectively. The first bora (21 March) was caused by a cold air outbreak arriving in the western Mediterranean region, followed by the Genova cyclogenesis process. On 23 March the cyclone was moving to the SE whereas simulataneous intensification of the anticyclone over the central Europe brought the cold NE airstream on the upstream of the Dinaric Alps, resulting in the bora of 22-25 March.

Despite the longest bora duration in Senj, the maximum gust refers to 23 March at Rijeka airport - Omišalj (31 ms^{-1}). The maximum gust at Senj occurred on the next day (27 ms^{-1}). On the last day of the period under consideration, the bora remained only in Senj with moderate intensity.

As seen in Fig. 2, two maxima in wind speed give the values of pressure differences between Ogulin, on the windward side, and Rijeka airport-Omišalj in the lee side. The largest pressure difference (8.4 hPa) occurred during the strongest bora on 23 March.

The space differences in bora speed and direction demonstrate the mesoscale analysis for 21 and 24 March in Fig. 3. Accumulated cold air in the inland was blocked and caused the pressure increase on windward side. The streamline field analyses suggest that the downward moving air particles from Velebit would change direction sharply at the sea level to the NNE. Over the Istria there is a divergence in a streamline field, and in Pula eastern wind component prevails.

We want to point out the existence of a region with a very weak wind estending from the NE of Pula over Cres Island towards Rab Island to the SE: The existence of such zones can be ascribed to the local effects and probably to wavestreaming on the lee side of the Dinaric Alps.

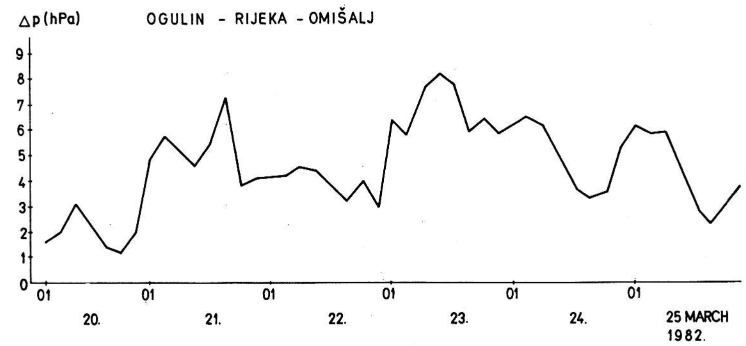

Fig. 2. Pressure difference Δp (hPa) between Ogulin and Rijeka-Omišalj from 20 to 25 March 1982.
Sl. 2. Razlika tlaka Δp (hPa) između Ogulina i Rijeka-Omišalj za 20-25.3.1982.

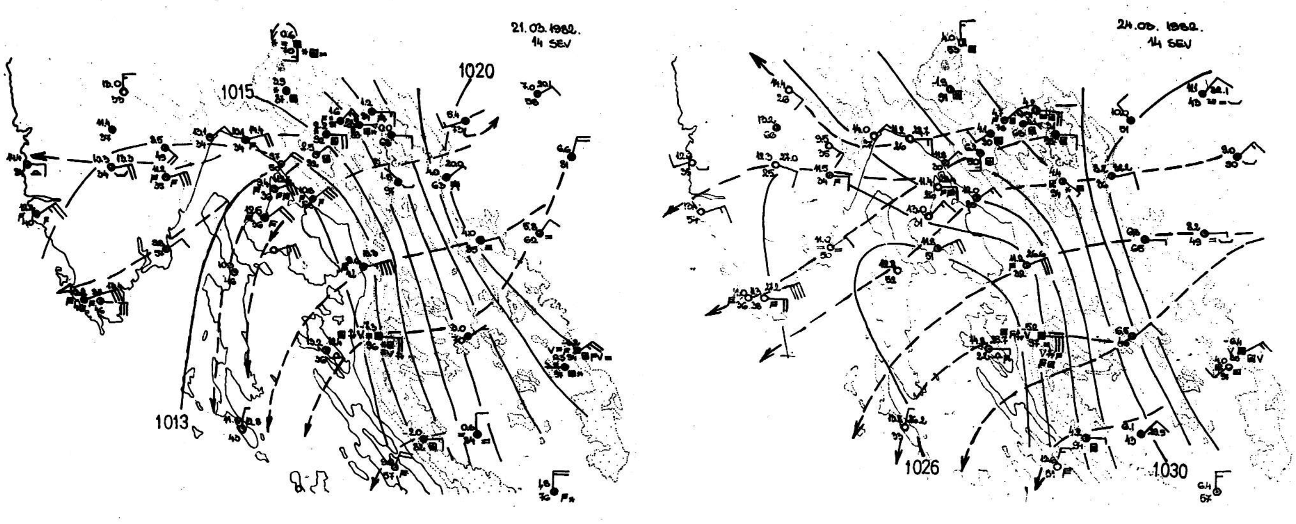

Fig. 3. Mesoscale analysis on the northern Adriatic on: a) 21 March 1982, 13 GMT b) 24 March 1982, 13 GMT. Solid lines are isobars and dashed lines are streamlines.
Sl. 3. Mezoanaliza na sjevernom Jadranu za: a) 21.3.1982, 13 GMT b) 24.3.1982, 13 GMT Pune linije su izobare, a crtkane linije su strujnice.

3. VERTICAL STRUCTURE OF THE ATMOSPHERE

A detailed analysis of the fields of wind and temperature in the low troposphere up to 3 km for Zagreb and Pula during the situation under consideration, can be found in Vučetić (1984). The time-height cross-section with 3-hr intervals shows the normal daily course of temperature in the low tropospheric layer. The wind up to 3 km is mainly NE with significant variability in speed (Fig. 4). Wind speed does not generally differ greatly between Pula and Zagreb, but the maximum always appear in Zagreb at higher altitudes than in Pula. Fig. 4 also exhibits vertical distribution in moisture (mixing ratio), which also shows variation in space and time. The situation under consideration shows little difference between the coast region and the upstream bora region, in contradiction to bora of 5-7 March and 14-15 April having higher values of mixing ratio over the coast.

NE streaming of 22 and 25 March throughout the troposphere is rather unusual in bora periods. Consequentily, it is difficult to determine the height of the bora layer on the basis of wind speed and direction only. Thus, in a unidirectional bora case it is only the inversion layer by which the bora depth could be determined.

The vertical profiles of potential temperature suggest that most of the stability in the incoming flow was concentrated in an inversion between 3 and 4 km (Fig. 6). The last day of the bora period, 25 March, the bora weakened. The supply of cold air was nearly zero as evidenced by the shallow weak inversion (1850-2100 m) in Zagreb.

The square of Brunt-Väisällä frequency N^2 is proportional to static stability of the atmosphere. Therefore, vertical time cross-sections for N^2 at Zagreb, Karlovac, Pula and Zadar are shown (Fig. 7). On 22 March the upstream stable layer existed continuously about 3 and 4 km altitudes. While the bora was weakening (25 March) this layer descended at about 2 km altitude.

The bora end on 25[th] of March (exept in Senj) may be ascribed to the descent of the temperature inversion. This could explain the longest duration and the stronger bora in Senj as a consequence of its specific location near the Vratnik Pass with lower mountain height and a low temperature inversion below the surrounding mountain top levels. The strong upper tropospheric NE flow

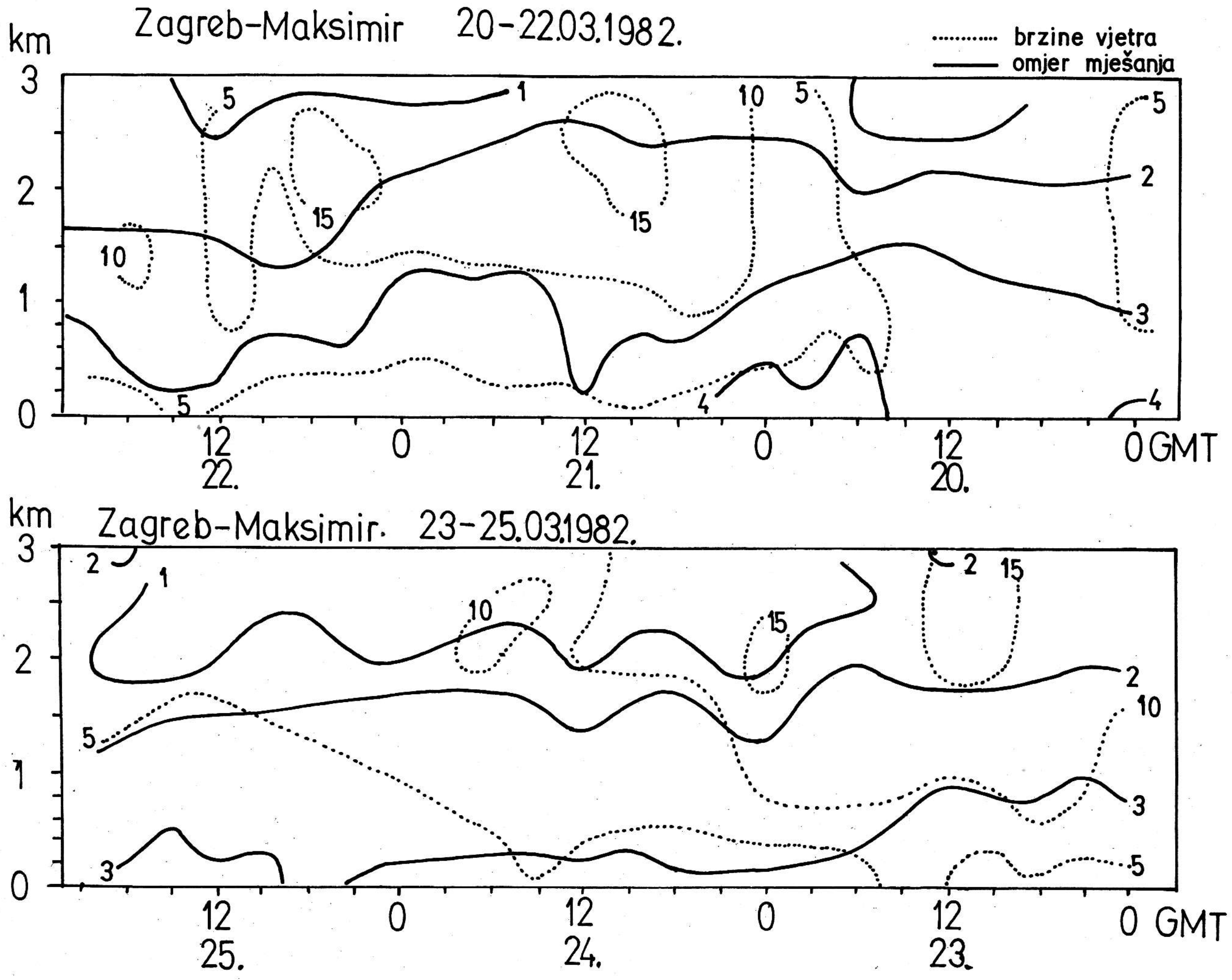

Fig. 4. Time height cross section over Pula and Zagreb. Solid lines are mixing ratio (gkg^{-1}) and dashed lines are isothach (ms^{-1}).

Sl. 4. Vertikalni vremenski presjek za Pulu i Zagreb. Pune linije su izolinije omjera miješanja (gkg^{-1}) i crtkane linije su izotahe (ms^{-1}).

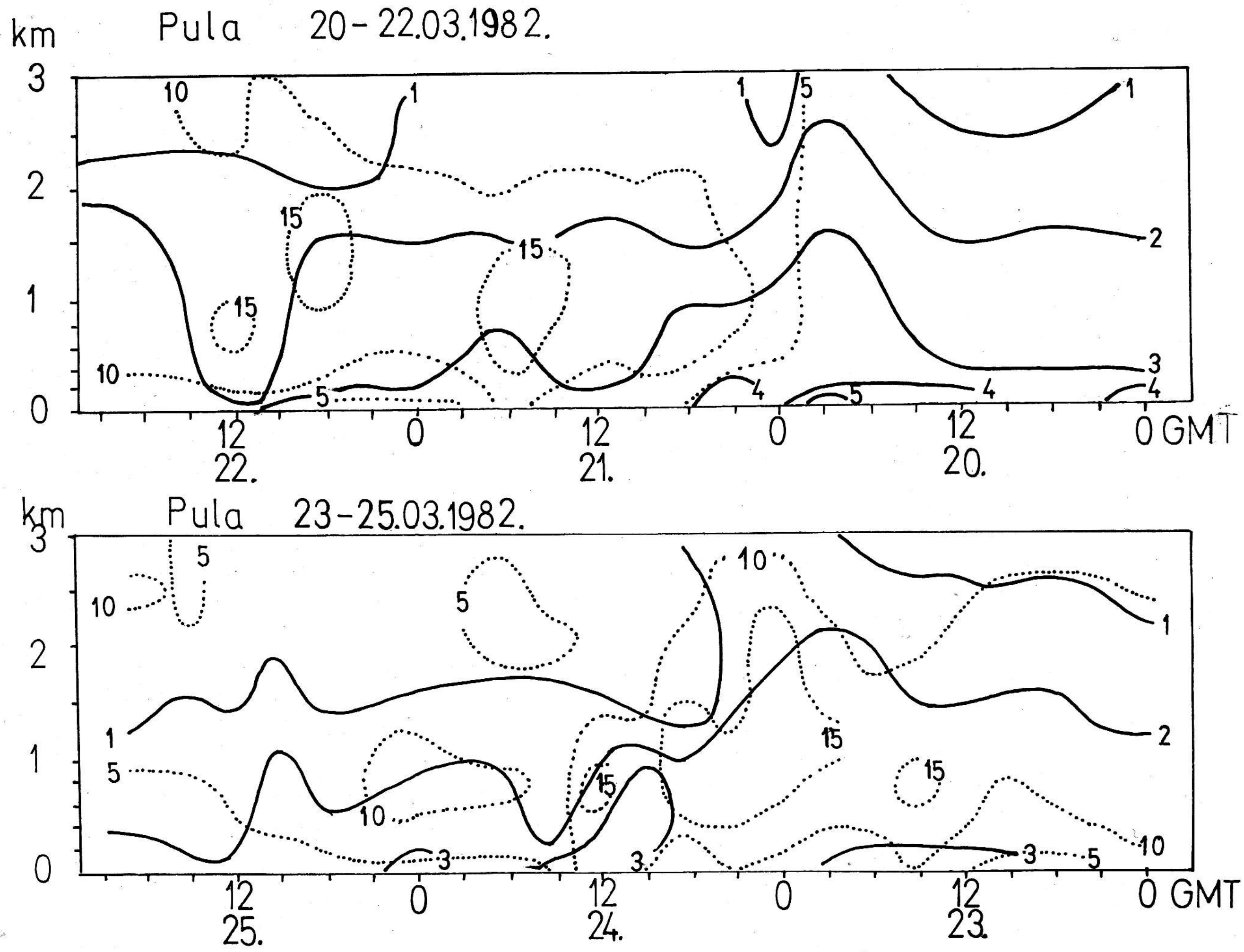

Fig. 4. Continuation
Sl. 4. Nastavak

destroyed the temperature inversion and the bora stopped, even in Senj.

Vertical wind structure throughout the troposphere shows a pronounced time and space difference in velocity. In the period 21-24 March the maximum of wind speed was located in the lower troposphere, generally higher at Zagreb than at Pula, and the wind speed aloft weakened. The low troposphere winds on the last day, 25 March, were weaker than in the higher troposphere (Fig. 8). It seems therefore, that the maxima bora speeds occur under a condition of weaker tropospheric winds, while the bora is weakening with increasing unidirectional winds in the upper troposphere.

The bora of 20-25 March was dry, predominantly NE flow extending almost throught the whole troposphere. The last day, 25 March, is characterized by increased humidity in the 650 to 500 hPa layer. Increased humidity allowed the formation of wave clouds. This visual proof of the nature of the flow is given by the visible satellite image in Smith (1987). The photograph from ELECTRA (E 325) indicates two levels of wave clouds, thus allowing vertical propagation of mountain waves for the NE flow above the bora layer.

4. APPLICATION OF HYDRAULIC THEORY

In the issue RASPRAVE-PAPERS 23 (Bajić, Jurčec, Vučetić, Tutiš) the results of several ALPEX bora case studies were presented including the aplication of Smith–s (1985) theory. The results indicate a considerable agreement.

According to hydraulic theory (Long, 1954) strong winds will occur along the lee slope when the fluid undergoes a transition from the subcritical flow upstream to the supercritical flow over the mountain.

This analysis of the bora cases indicate at least two major upstream flow types:

1. The first group includes all cases when there is a strong inversion layer above the cold, nearly neutrally stratified, low level air which could behave like the discontinuity in density at a layer interface as described by hydraulic theory (Long, 1954).

2. The second group includes all cases when we cannot apriori determine the bora layer depth because the upstream flow is continuously stratified (Smith, 1985, 1987).

The same comparison of upstream conditions with

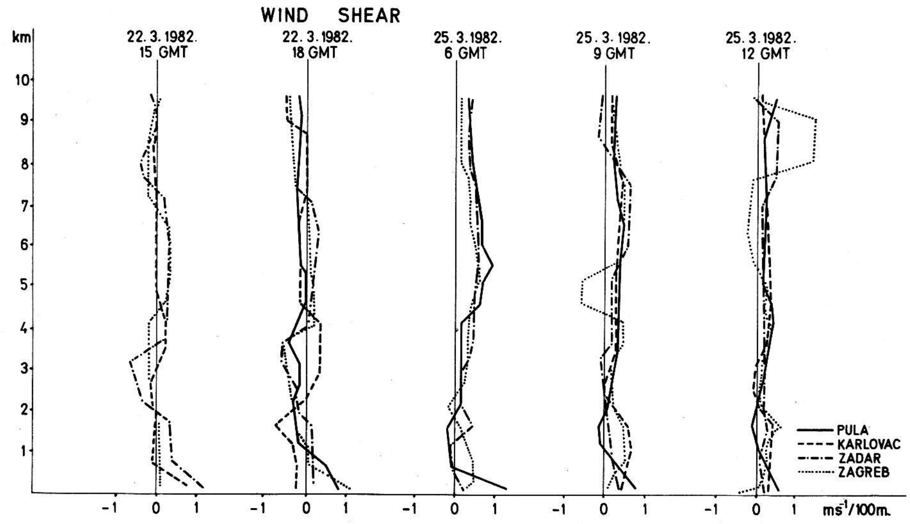

Fig. 5. Vertical profiles of wind shear over Zagreb, Karlovac, Pula and Zadar during the aircraft data analyses.
Sl. 5. Vertikalni profili smicanja vjetra za Zagreb, Karlovac, Pulu i Zadar za vrijeme avionskih mjerenja (22. i 25.3.1982).

prediction of hydraulic theory is done here on 21-25 March. The monutain height is 800 m as in Smith–s paper.

NE upper flow of a considered period throughout the troposphere is rather unusual for the bora occurrence. Consequently, it is difficult to determine the height of the bora layer H_0 on the basis of wind speed and direction only. In our situation we have taken into consideration the level where the NE "bora component" (45° ± 90°) was positive, and $u_B = 0$ is identical with H_0 in Smith (Fig. 8). The vertical profiles of Brunt-Väisälä frequency proportional to static stability of the atmosphere at Zagreb are shown (Fig. 8). When the upper layer becomes thin in comparison with the total depth the problem reduces to a single layer model (Long, 1954). Such situations were noticed on 22 and 25 March where the lower neutral layer extended from the ground to an altitude of about 3.5 and 2 km, respectively. Above this there was a thin but very strong stable layer ($N=3*10^{-2} s^{-1}$). In the period 21 - 24 March the bora was the strongest and the upstream stable layer existed continuously at about 3 - 4 km altitudes.

While the bora was weakening (25 March) this layer descended at 2 - 3 km altitude. Thus just in the flight cases (22 and 25 March) the $u_B \neq 0$ extended throughout the troposphere. On these days the problem reduced to a single layered type, for which the critical mountain height for transition flow is given by the Long (1954) relation:

$$\frac{h}{H_0} = 1 + \frac{1}{2}F_0^2 - \frac{2}{3}F_0^{2/3} \qquad (1)$$

(see Grubišić, 1989).

On 21,23 and 24 March the low troposphere could be considered as continuously stratified and therefore we can follow Smith (1985, 1987) in the calculation of the height of the dividing stremline and Froude number $F_0 = U/NH_0$ for the continuous type. The theoretical value of the critical layer H^*_0 for critical mountain height is obtained by:

$$\hat{H}_0^* = \hat{h}^* - \hat{\delta}^* + \arccos\frac{\hat{h}^*}{\hat{\delta}^*} \qquad (2)$$

The observed and calculated hydraulic parameters are given in Table 1 according to radiosounding data of Zagreb. The comparison of upstream conditions with the predictions of hydraulic theory is shown in Fig. 9.

The predicted H^*_0 is lower for 2.53 km than the empirical H_0. This large difference was found for 22 March. The predicted H^*_0 is in most cases lower than the subjective H_0 defined by the u_B component which seems reasonable.

Only for 23 March the predicted H^*_0 is higher by 2.37 km than the subjective H_0. This day had the maxima gust on the north Adriatic (31 ms^{-1} at Rijeka airport, Krk).

The small theoretical and empirical Froude numbers are rather close and indicate the possibility of hydraulic jump on the downstream bora region.

The value of $\hat{h}$ is known to play a role in steepening and wave breaking. According to Miles and Huppert (1969) if $\hat{h}$ is in the range of $0 \leq \hat{h} \leq 0.85$ the internal waves generated by the flow over the barrier will not break (or will not be supercritically steepened). The transitional flow for $\hat{h}>1$ for Smith's model (1985) is not possible. Such bora conditions were noticed on 22, 24 and 25 March when bora ceased at most places except in Senj.

If we specify $\hat{h} = 1$, for considered bora conditions the predicted maximum height of the mountain is about 600 m. This results indicates the transient flow over lower passes and may explain the longest bora duration in Senj.

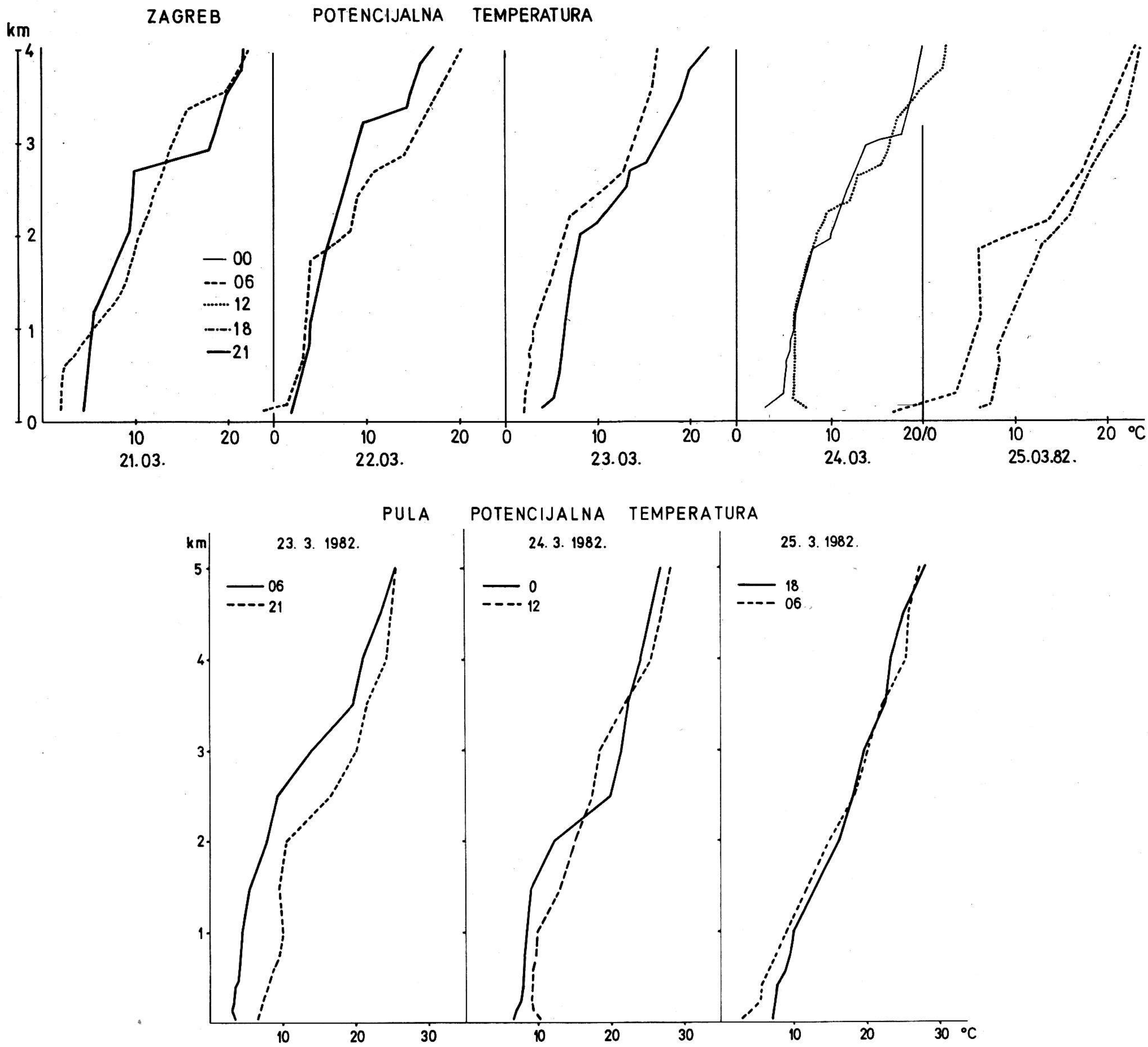

Fig. 6. Vertical profiles of potential temperature for Zagreb and Pula in selected situations.
Sl. 6. Vertikalni profili potencijalne temperature za Zagreb i Pulu u odabranim situacijama.

The hydraulic theory (Smith, 1985) appears to be the most pertinent for the period with the strongest bora on the northern Adriatic (21 and 23 March).

Although it seems that hydraulic theory offers some satisfactory suggestions on the dynamical mechanism of the bora, there are still a lot of details which should be included in some general bora theory. For example, three dimensional effects, surface friction and quick movement or exchange of synoptic features strongly affect the real bora flow.

5. CONCLUSION

The case studies of a bora event on 20-25 March indicated the following characteristics:

1.Two bora periods 21-22 March and 23-25 March had different origins of bora genesis. The first situation was preceded by cyclogenesis in the Gulf of Genoa. The second bora event is connected with the central European anticyclone and a cold NE flow in the upstream bora region.

2.In spite of the fact that the incoming flow on both 22 and 25 March was NE throughout the troposphere, there was an essential difference in vertical wind speed profiles on these days. While the maximum bora speed on 22 March occured in the low troposphere, the decrease of bora on 25 March was followed by a strengthening of the upper tropospheric NE winds.

3.The bora end on 25th of March (except in Senj) may be ascribed to the descent of the temperature inversion. This could explain the longest duration and the stronger bora in Senj as a consequence of its specific location near the Vratnik Pass with lower mountain height and a low temperature inversion below the surrounding mountain top levels. The strong upper tropospheric NE flow destroyed the temperature inversion and the bora stopped, even in Senj. A comparison of this particular situation with the other ALPEX bora cases leads to the conculsion

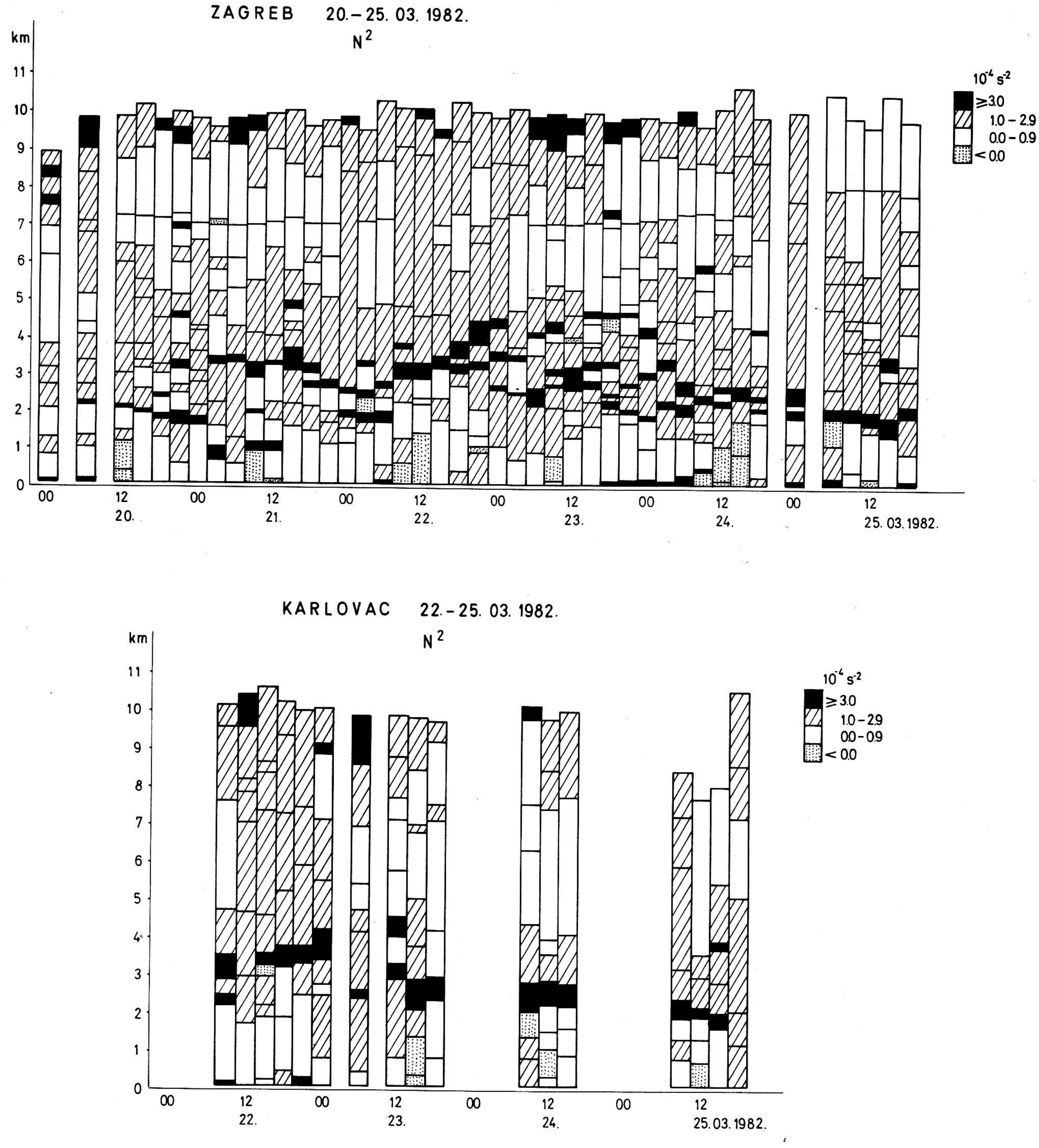

Fig. 7. Time-height cross section of Brunt-Väisälä frequency (N^2) during 20-25 March over Zagreb and Karlovac.
Sl. 7. Vremenski vertikalni presjek Brunt-Väisälä frekvencije (N^2) u periodu od 20-25.03.1982. za Zagreb i Karlovac.

that bora on the northern Adriatic ceases due to strengthening of the upper NE tropospheric wind.

4.The hydraulic theory (Smith, 1985) appears to be the most pertinent for the period with the strongest bora on the northern Adriatic (21 and 23 March).

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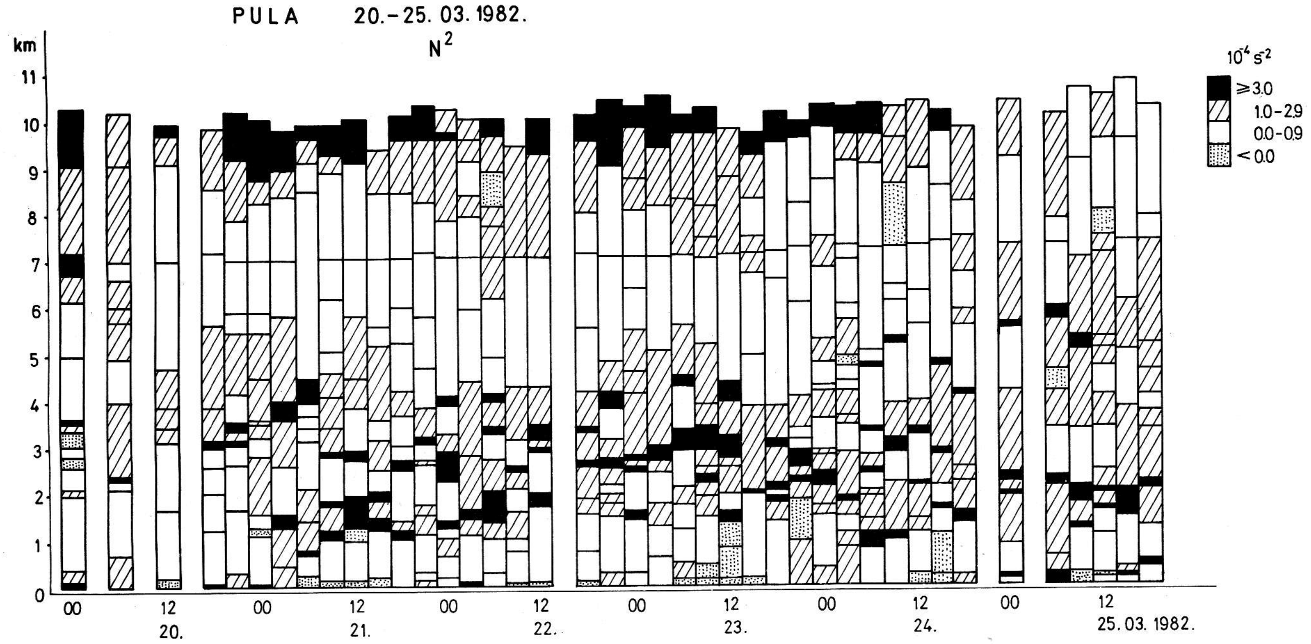

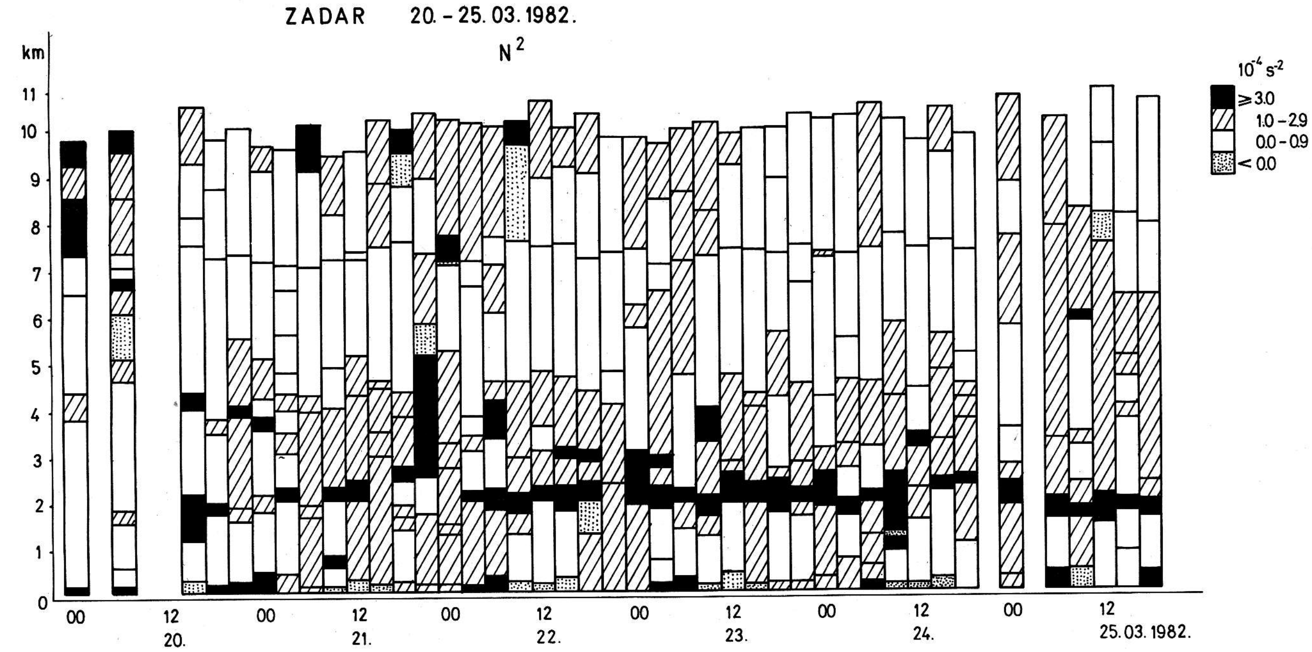

Fig. 7. Continuation
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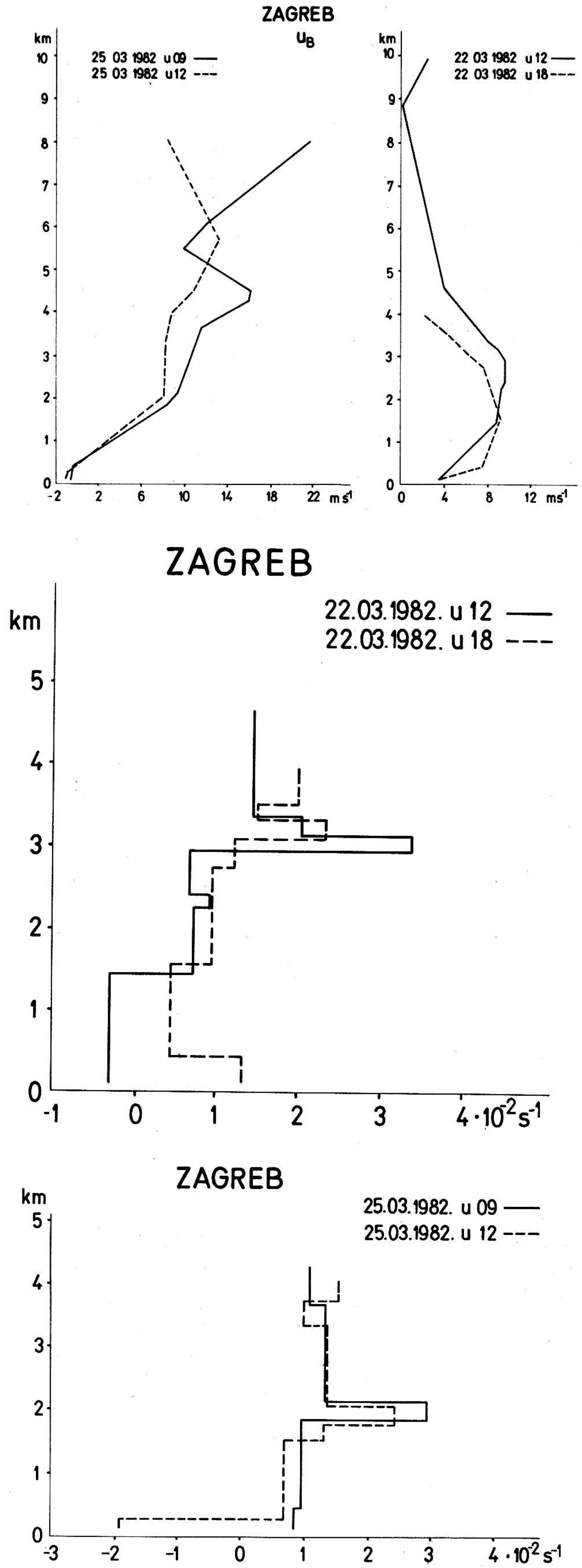

Fig. 8. **Vertical profiles of stability and u_B wind component over Zagreb on 22 and 25 March 1982.**

Sl. 8. **Vertikalni profili stabilnosti i u_B komponente vjetra za Zagreb za 22. i 25.03.1982.**

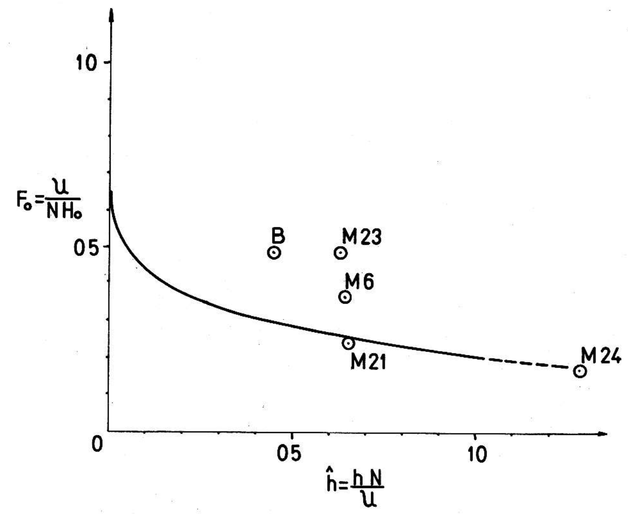

Fig. 9. **A comparison of upstream conditions with the prediction of Smith–s (1985) model. Points M6 and B are overtaken from Smith (1987). M21, M23 and M24 represents March 21, 23 and 24 1982, respectively. Data are taken from Table 1.**

Sl. 9. **Usporedba prognoze Smithovom teorijom (1985). Točke M6 i B su preuzete od Smith (1987). M21, M23 i M24 odnose se pojedinačno na 21, 23. i 24.3.1982. Podaci se nalaze u Tabeli 1.**

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KRATKI SADRŽAJ

Proučavanje pojave bure u periodu 20-25.03. ukazuje na slijedeće karakteristike:

1.Dva odvojena maksimuma brzine vjetra ukazuju na dva različita uzroka nastanka bure. Prva situacija (21.-23.03.) uvjetovana je ciklogenezom u Genovskom zaljevu. Druga pojava bure (23.-25.03.) povezana je s anticiklonom nad srednjom Evropom i hladnim NE strujanjem u navjetrini Dinarida.

2.Usprkos činjenici da je strujanje u navjetrini i 22. i 25.03. kroz cijelu troposferu NE smjera, postoji bitna razlika u vertikalnim profilima vjetra. Dok se maksimum brzine bure 22.03. pojavljuje u nižoj troposferi, slabljenje bure 25.03. je posljedica jačanja NE vjetra u višoj troposferi.

3.Slabljenje bure 25.03. (osim u Senju) posljedica je spuštanja temperaturne inverzije. Zbog specifičnog položaja u blizini Vratnika, gdje je visina prepreke niža i spuštanje inverzije u blizinu planinskog vrha, bura u Senju najdulje puše. Jačanjem NE troposferskog vjetra inverzija se dalje razara i bura prestaje i u Senju. Usporedba ove

Table 1. Hydraulic parameters for period 20-25 March 1982 according to sounding of Zagreb.
Tabela 1. Hidraulički parametri za period 20- 25.03.1982. prema radiosondažnim podacima Zagreb.

Date	CONTINUOUS STRATIFICATION									
	h [m]	$\hat{h}$	N [s^{-1}]	U [ms^{-1}]	I [$10^{-3}m^{-1}$]	H_0 [m]	F_0	δ^* [m]	H_0^* [m]	F_0^*
21 March 09GMT	800	0.65	0.009	11.4	0.807	5090	0.24	-1190	4860	0.25
23 March 12GMT	800	0.62	0.009	11.7	0.769	2650	0.49	-1320	5020	0.26
24 March 03GMT	800	1.28	0.012	7.7	1.595	5540	0.16	-960	3370	0.27
20-22 March	800	1.19	0.012	7.8	1.487	4400	0.15	-980	3480	0.19
23-25 March	800	1.08	0.013	9.1	1.352	4250	0.17	-1000	3650	0.20

Date	SINGLE LAYER										
	h [m]	$\hat{h}$	N_2 [s^{-1}]	U [ms^{-1}]	I [$10^{-3}m^{-1}$]	H_0 [m]	F_0	h/H_0	H_0^* [m]	F_0^*	$(h/H_0)^*$
22 March 15 GMT	800	2.23	0.020	7.0	2.794	4070	0.19	0.20	1540	0.48	0.52
25 March 09 GMT	800	4.64	0.029	5.0	5.800	2130	0.22	0.38	1670	0.25	0.48

situacije s drugim ALPEX periodima s burom vodi do zaključka da bura na sjevernom Jadranu slabi jačanjem NE vjetra u višim slojevima troposfere.

4.Hidraulička teorija (Smith, 1985) na području sjevernog Jadrana najbolje opisuje mehanizam bure za vrijeme dok je bura najjača (21 i 23.03).